Limits of Collective Motion in Hot Nuclear Matter

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High-energy γ-ray spectra have been measured in coincidence with products from the reaction $^{40}Ar + ^{70}Ge$ at 15 and 24 MeV/nucleon. The evolution of the giant dipole resonance is studied as a function of excitation energy (E^*). Up to $E^* \approx 300$ MeV the measured giant dipole resonance strength is consistent with full collectivity. At higher E^* a strong inhibition of the giant dipole resonance γ decay is observed. At the highest transition energies, the spectra are consistent with bremsstrahlung emission associated with nucleon-nucleon collisions.

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The spectrum of nuclear excitations at low temperatures is a direct manifestation of the quantal nature of nuclear matter. It reflects the possibility of storing energy through excitations of individual particles as well as in collective motion of the nucleons. With increasing temperature the nuclear level density grows exponentially and the excitations must be treated statistically. The presence of collective excitations in nuclear matter up to temperatures of a few megaelectronvolts is now well established through the study of the γ decay of giant dipole resonances (GDR's) built on excited states.[1-3] The damping of these excitations can be understood in terms of couplings to other collective degrees of freedom, such as the shape,[1,4,5] and can be calculated with methods developed to describe the low-temperature spectrum.[6] Nevertheless, it is neither clear whether this picture of the excitation and damping of nuclear collective modes can be applied at temperatures up to those at which the individual nucleons become unbound, nor whether collective excitations persist at all. In a recent study,[7] the GDR was observed in high-energy γ-ray spectra following reactions at 44 MeV/nucleon, although it was ascribed to the decay of targetlike fragments excited to $E^* \approx 90$ MeV ($T_{max} \approx 2.2$ MeV) in peripheral collisions.

In this Letter we report on the first measurements of high-energy γ rays in which the decay is restricted to evaporation residues that have been excited to energies as high as 600 MeV. For residues with $E^*_{max} \approx 360$ MeV, the spectrum in the GDR region ($E_\gamma \approx 15$ MeV) can be understood in terms of the statistical decay of collective dipole states built on excited states in an equilibrated system populated with approximately the full E^* which can be transferred to the compound system. This indicates the persistence of collective nuclear motion up to temperatures $T \approx 3.5$ MeV. In contrast, at a higher internal energy ($E^* \approx 610$ MeV), the observed γ-ray yield from the GDR fails to increase as would be expected for the much higher E^* available for the decay. In fact, the γ-ray spectra measured at the two bombarding energies and in coincidence with fused recoils originating from compound systems around ^{110}Sn are essentially identical in shape and strength in the energy range of the GDR (after subtraction of the respective bremsstrahlung components), which suggests an inhibition of the γ decay above $E^* \approx 300$ MeV. Furthermore, the structure of the observed GDR differs from the one previously studied up to $E^* = 130$ MeV,[1,2] which suggests a reduced resonance width.

The experiments were done with use of the coupled cyclotron facility SARA, at the Institut des Sciences Nucléaires, Grenoble, bombarding 1-mg/cm^2 ^{70}Ge targets with ^{40}Ar beams of 15 and 24 MeV/nucleon. The high-energy γ rays were measured in an array of six (12 cm diam by 17 cm) NaI detectors, shielded with 4 cm of lead and equipped with 6-mm Pb and 20-mm neoprene absorbers to minimize the count rate due to low-energy transitions and from charged particles. The detectors were located at a backward angle (160°) relative to the beam direction and 45 cm from the target, thereby permitting discrimination against neutron-induced events by a measurement of the time of flight to the detectors relative to the beam burst (width 1–2 ns). The reaction products were detected in two position-sensitive parallel-plate avalanche counters (PPAC's) (15×20 cm^2) placed on either side of the beam in the forward direction and covering an angular range of approximately 3–20°. The PPAC's provided a measurement both of the time of flight of the particles and of their energy loss (charge). An event was defined by a coincidence between one γ ray above 6 MeV and a heavy particle. The NaI detectors were calibrated with a Pu^{13}C source (E_γ=6.13 MeV), and cosmic rays for a high-E_γ reference point.

In Fig. 1 we show γ-ray spectra measured in coincidence with detected particles corresponding to central and peripheral collisions for the two bombarding energies. The respective particle gates are indicated in Fig. 2 which shows the energy loss of the particles in the PPAC's as a function of their time of flight from the target. The measured flight times for the heaviest particles detected are consistent with those expected for recoiling nuclei following complete fusion (CF). All γ-ray spectra have been corrected for Doppler shifts assuming emission from a source moving with the center-of-mass velocity $V_{\mathrm{c.m.}}$. With increasing bombarding energy the proportion of incomplete fusion (IF) increases. This is consistent with measured values of the linear momentum transfer as a function of projectile energy,[8] which indicate the onset of significant IF around 15 MeV/nucleon. The maximum E^* transferred to the composite system, for the CF gates, is thus $E^*_{\max}=360$ and 610 MeV, respectively. The widths of the gates correspond to an E^* distribution extending downward 10%–20% from these values. For the 24-MeV/nucleon reaction the application of a narrower gate around $V_{\mathrm{c.m.}}$ yields a practically identical γ-ray spectrum. For the spectra gated by fast beamlike particles it is not clear which fragment emits

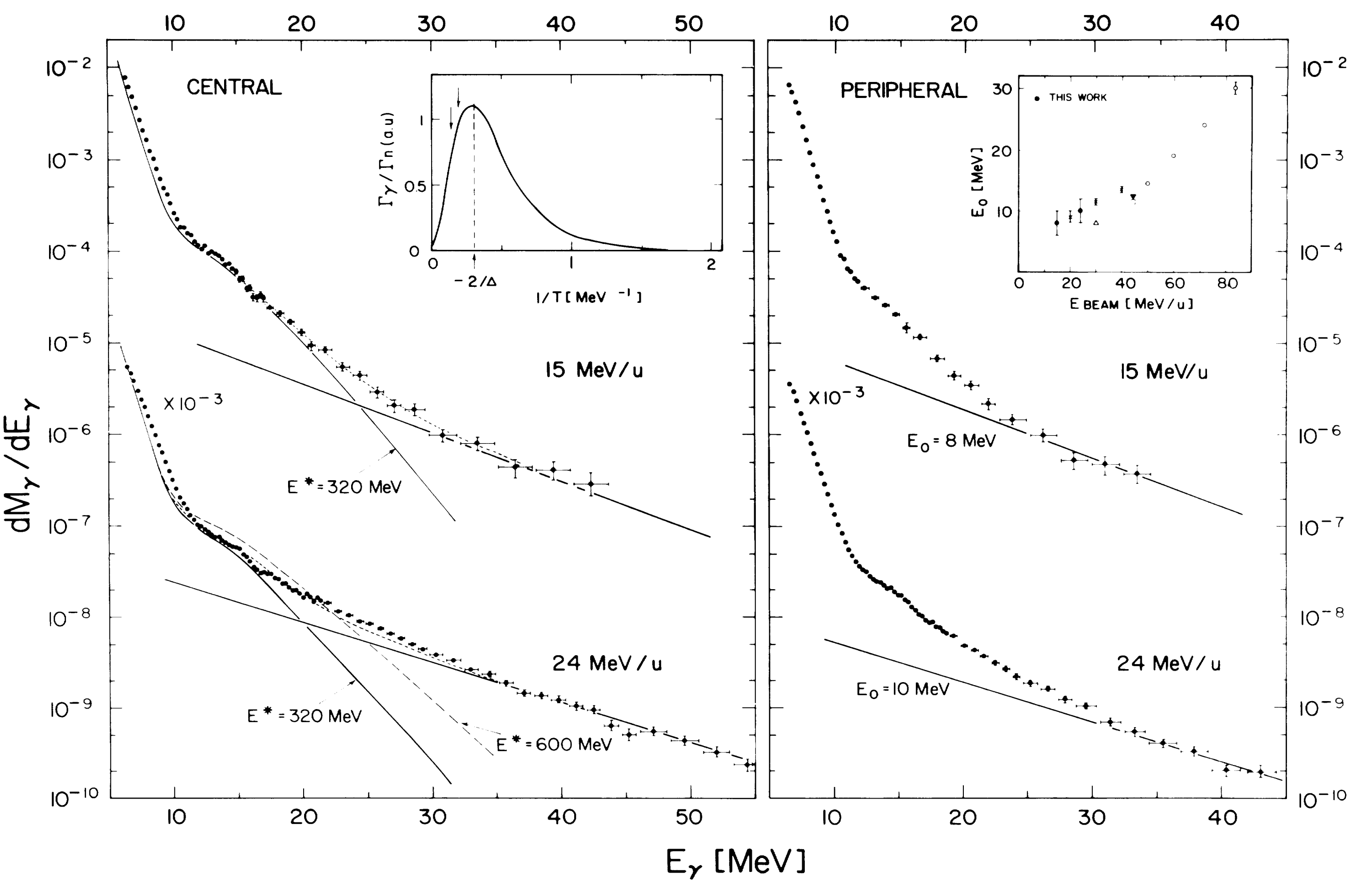

FIG. 1. γ-ray spectra for the reaction ^{40}Ar+^{70}Ge at 15 and 24 MeV/nucleon. The spectra correspond to complete fusion (left) and peripheral collisions (right) as determined by the particle gates indicated in Fig. 2. Note that the spectra have been corrected for Doppler shifts assuming emission from a system moving with the center-of-mass velocity. The lines correspond to statistical model calculations (thin solid: $E^*=320$ MeV; dashed, $E^*=600$ MeV; and dotted, statistical calculation + bremsstrahlung). The inverse slopes, E_0, of the bremsstrahlung contribution are indicated. Insets: The temperature dependence of the γ-to-particle branching ratio and the systematics of the bremsstrahlung slope parameters.

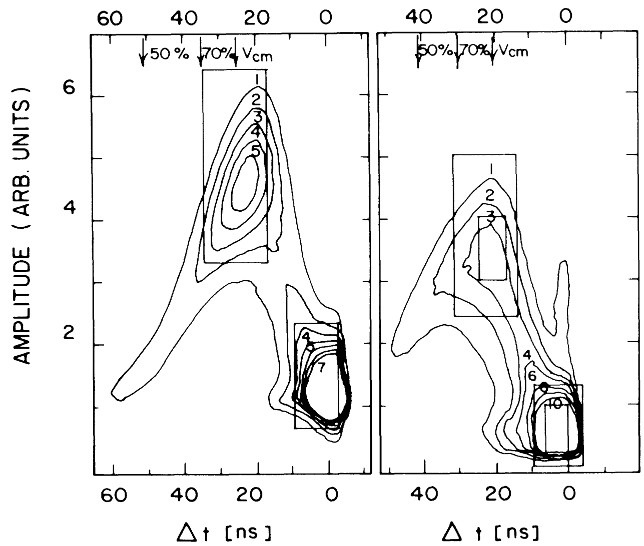

FIG. 2. Distribution of the energy loss of particles detected in the two PPAC's used in the experiments, as functions of time of flight from the target. The gates used in the analysis for generating the coinicident γ-ray spectra are indicated.

the γ radiation nor is the (lower) E^* well defined. The high-energy part (above $E_\gamma \approx 35$ MeV) of the 24-MeV/nucleon spectrum corresponding to central collisions can be fitted with an exponential curve as shown in the figure. The extracted inverse slope, $E_0 = 10 \pm 2$ MeV, is in agreement with the systematics for bremsstrahlung spectra obtained from (mostly inclusive) reactions at higher bombarding energies. The inset in the right-hand side of Fig. 1 depicts the results compiled from the literature (see Bertholet *et al.*[9] and references therein). These measurements are consistent with bremsstrahlung originating from nucleon-nucleon collisions and are in qualitative agreement with microscopic phase-space calculations for first-chance nucleon-nucleon collisions.[10] With increasing impact parameter, the slope appears practically unchanged as can be seen by transferring the deduced slope for the central collisions onto the spectra corresponding to the peripheral collisions (right-hand side of Fig. 1), but the γ-ray yield is reduced by a factor close to 5. This is consistent with the smaller geometrical overlap of the collision partners. Below $E_\gamma = 9$ MeV the slopes of the spectra are almost identical, reflecting statistical γ-ray emission from the broad distribution of residual nuclei at very low excitation energy. For the spectra at 15 MeV/nucleon the experimental statistics at high transition energies are not sufficient to allow a determination of the bremsstrahlung slope.

Also shown in Fig. 1 (for the CF gates) are calculations of expected γ-ray spectra with the assumption of a statistical deexcitation of equilibrated Sn nuclei at various initial E^*. The dipole strength function is taken as a Lorentzian function with centroid $E_{\mathrm{GDR}} = 15.5$ MeV, width $\Gamma_{\mathrm{GDR}} = 15$ MeV, and full energy-weighted sum-rule (EWSR) strength. For the 15-MeV/nucleon reaction a calculation, folded with the detector response function and assuming that $E^* = 320$ MeV, reproduces the observed γ-ray multiplicities per reaction up to $E_\gamma \approx 20$ MeV. The shape of the calculated spectrum depends on the nuclear level density, an essentially unknown quantity at these temperatures. Here, we have used the value $a = A/8$ which is appropriate for describing the GDR spectra measured up to $E^* \approx 130$ MeV.[1-5] This analysis indicates that collective resonances persist in nuclear systems formed with 3–4 MeV of E^* per particle, and supports the premise of decay from a system in thermal equilibrium. A subtraction of this calculated spectrum from the data yields an exponentially decreasing γ-ray component which becomes dominant at the highest transition energies (Fig. 1; the sum of the two components is indicated with a dotted line). The inverse slope is $E_0 = 8 \pm 2$ MeV, and in general agreement with available bremsstrahlung systematics.

In contrast with expectations (and calculations) the γ-ray yield in the giant-resonance region is nearly identical for the 15- and 24-MeV/nucleon data. This yield is expected to increase with increasing E^* because of the larger number of chances for γ rays to compete with particle decay. Indeed, a calculation with $E^* = 600$ MeV (the maximum possible E^* transfer is 610 MeV), $a = A/8$, and 100% EWSR for the GDR decay grossly overpredicts the observed γ-ray yield. Even though the γ width relative to that for particle emission saturates at $T_{\max} = (E_{\mathrm{GDR}} - S_n)/2$, i.e., at 3–4 MeV for this mass region (see the inset in Fig. 1 for $E_\gamma = 15$ MeV), this cannot explain the observed strength reduction. Although a decrease of the transferred E^* relative to the maximum value is expected, because of the onset of incomplete fusion, a satisfactory description of the spectrum can only be achieved if we assume an E^* close to that appropriate for the 15-MeV/nucleon spectrum (thin solid line in Fig. 1), i.e., about half the maximum possible E^*. The systematics of the average momentum transfer in central collisions indicate no more than 20% loss at these bombarding energies.

These data consequently indicate a strong inhibition of the γ decay from the highest excitation energies. The recently suggested[11] decrease of nuclear level densities with increasing temperature is a possible mechanism for such an inhibition. However, reduction of the level-density parameter from $a = A/8$ to the hot-Fermi-gas limit ($a = A/15$) in the calculations for $E^* > 320$ MeV will only reduce the additional γ-ray yield from the upper decay steps by a factor of 2. Thus the discrepancy can be reduced, but not fully accounted for.

In Fig. 3 we show the 24-MeV/nucleon spectrum (CF gate), from which the bremsstrahlung component has

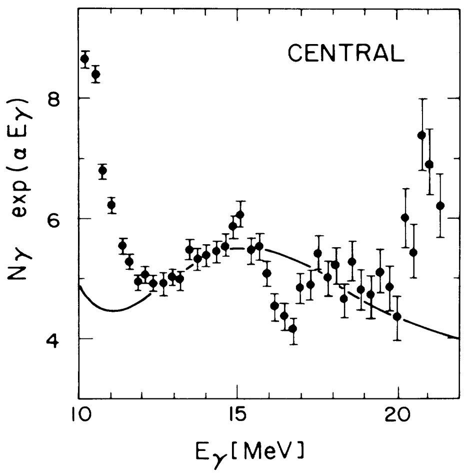

FIG. 3. Spectrum with complete fusion from the 24-MeV/nucleon reaction after subtraction of the bremsstrahlung component, and multiplied by $\exp(E_\gamma/3)$. The statistical calculation assumes $E^* = 320$ MeV and $\Gamma_{GDR} = 15$ MeV.

been subtracted. The spectrum has been multiplied by $\exp(E_\gamma/3)$ in order to emphasize the details in the GDR region. Also shown is the statistical calculation ($\Gamma_{GDR} = 15$ MeV, $E^* = 320$ MeV) multiplied by the same function. It is apparent that the observed structure of the GDR is not adequately described by a single Lorentzian component centered at $E_{GDR} = 15.5$ MeV with a width of 11–12 MeV as is found for the decay of $^{108-111}$Sn isotopes formed at $E^* = 100-130$ MeV.[1,2] The data are not consistent with a continued strong increase in the GDR width with increasing temperature, which would spread the $E1$ strength. Rather, a reduced width is suggested.

These observations indicate that the empirical spectra can be decomposed into a part consisting of γ rays emitted in the initial phases of the reaction, corresponding to nucleon-nucleon bremsstrahlung, and a part related to the deexcitation of the nucleus. While the former is in good agreement with systematics extrapolated from higher bombarding energies, the latter shows new and striking features which relate to the properties of hot nuclear conglomerates. We may speculate as to possible explanations: (1) considerably enhanced particle decay widths at the highest E^* that reduce the γ-emission probability and deplete the available E^*, (2) loss of collectivity, related to a change from ordered to chaotic behavior, or (3) nonequilibration of the composite system, again resulting in a severe loss of collectivity until the system regains thermal equilibrium at lower temperature. We further note that recent theoretical investigations[12] suggest a reduced GDR width at higher E^* due to a motional narrowing effect similar to that responsible for the narrowing of the nuclear magnetic resonance. It thus appears that the region of E^* from 200 up to 400 MeV is particularly rich for study, raising questions regarding the validity of models based on thermal equilibrium for hot nuclear matter.

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